ARMY RESEARCH LABORATORY

Development of a Robust Static Punch Experiment for Screening Unprocessed Ultra-High Molecular Weight Polyethylene (UHMWPE) Unidirectional Cross-Ply Material

by David Gray, Robert Kaste, and Paul Moy

ARL-TR-7090 **September 2014**

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Weapons and Materials Research Directorate, ARL

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
September 2014	Final	January 2013–May 2014

4. TITLE AND SUBTITLE	
Development of a Robust Static Punch Experiment for Screening Unprocessed Ultra-High Molecular Weight Polyethylene (UHMWPE) Unidirectional Cross-Ply Material	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
David Gray, Robert Kaste, and Paul Moy	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
US Army Research Laboratory ATTN: RDRL-WMM-B Aberdeen Proving Ground, MD 21005-5066	ARL-TR-7090
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

At the request of the US Army Research Laboratory's Specifications and Standards Office, a novel experimental methodology for punch testing of Ultra-High Molecular Weight Polyethylene (UHMWPE) composites was developed. This test procedure will act as a quality-assurance test method and subsequently be an addendum to the new military specification MIL-DTL-32398. There are currently no intermediate mechanical testing methods to evaluate the production quality of new, unprocessed sheet material from UHWMPE manufacturers. Such methods are essential for assessing and predicting the acceptability of sheet goods prior to the curing/molding process relative to the product's ballistic performance. The primary challenge all laboratories face when testing unprocessed UHMWPE is gripping the slippery material to achieve repeatable data. We have designed and developed a relatively simple, cost-effective punch test procedure that addresses the issues associated with gripping UHMWPE composites during tests. A test protocol is presented that is simple, and the overall execution of the technique does not impose significant expense for test fixtures. This report details design iterations for the test fixture, specimen geometry, and gripping methods. Punch test results from the final fixture concept and experimental procedures have demonstrated repeatability for both load-displacement response and failure behavior in an unprocessed UHMWPE cross-ply composite sheet configuration.

15. SUBJECT TERMS

punch experiment, UHMWPE, punch resistance testing, static punch strength testing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			David Gray
					19b. TELEPHONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UU	26	(410) 306-0852

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

A novel punch test method was developed to support the ongoing efforts within the US Army Research Laboratory's Specifications and Standards Office to establish a new military specification, MIL-DTL-32398 "Laminate: Cross-Plied Ultra-High Molecular Weight Polyethylene (UHMWPE) Unidirectionally Reinforced Plastic Armor".[1] Currently there are no mechanical testing methods available to assess the quality of unprocessed, unidirectional cross-ply UHMWPE sheet material from the manufacturers' production lines. A quality-assurance (QA) test methodology is needed to provide insight into the effects of material variability on ballistic performance. The test protocol developed in this effort resembles ASTM D6241.[2] In addition, as a standard to determine the punch strength, this test protocol offers a relatively straightforward setup and cost-effective QA without the need for expensive test components. The ASTM D6241 standard utilizes a simple, supported test fixture that holds the coupon between 2 concentric plates with an internal diameter hole of approximately 5.9 inches and a flat-ended plunger about 2 inches in diameter.

Figure 1 is an adapted reference schematic of the ASTM D6241 test fixture and setup.

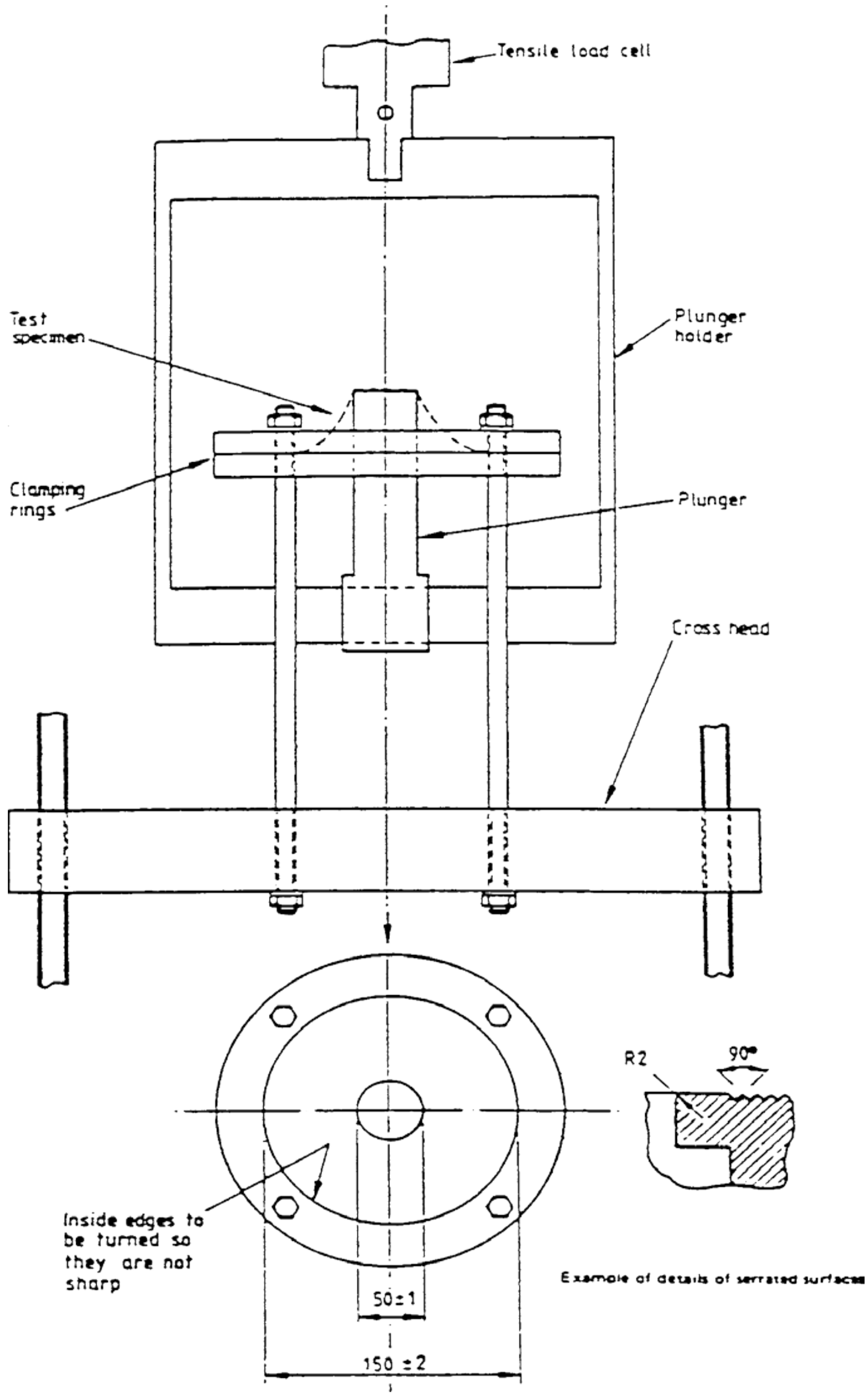

Fig. 1 Adapted reference schematic of ASTM D6241's punch-test fixture and setup

1.1 Initial Test Fixture Design

Based on the fundamental concept of the ASTM punch technique, which uses a round fixturing theory and produces insufficient grip for UHMWPE sheet coupons, a new test fixture with a square boundary condition was designed and fabricated that would help prevent the material from slipping during the applied punch loads. The square boundary conditions provide better support and facilitate loading of the UHMWPE cross-ply composite. The fixture comprises 2 steel plates with external dimensions approximately 9 inch × 9 inch with a 4 inch × 4 inch opening at the center. The bottom half of the plate is supported and bolted at each corner to four 1.5-inch diameter steel posts. This allowed the plates to be suspended and thus provides enough clearance for the punch to travel below the test fixture, if needed. A 0.375-inch diameter hemi-spherical groove was machined on the contacting surface for base plate. The grooves were about 0.5 inch from edge of the inner opening.

Figure 2 shows the engineering drawing of the bottom plate of the test fixture.

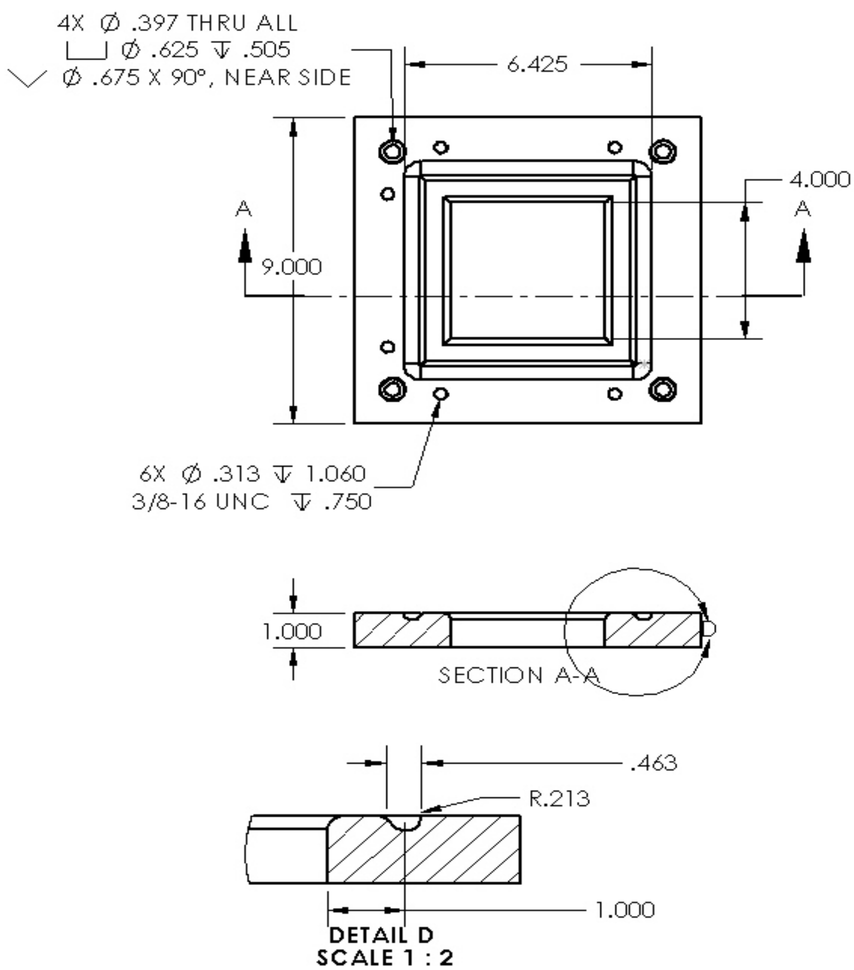

Fig. 2 Details of bottom plate of new UHMWPE test fixture

The unprocessed unidirectional cross-ply coupon is sandwiched between 2 plates similar to the ASTM D6241 procedure and then followed by a knurled rod that was placed in a slotted groove at all 4 sides. The length of the knurled rods was 6 inches. Since the UHMWPE sheet material is relatively pliable, the coupon was able to be wrapped under and over the knurled rod and then held down with the upper portion of the fixture. Figure 3 provides a cross-sectioned view of the coupon clamped between the top and bottom plates. This provides a high pinch force to mitigate slippage. However, experimental results from this initial concept proved only partially successful with some slippage occurring. Another contributing factor for the slippage is the coupon geometry utilized. ASTM D6241 references a requirement of 10 mm (0.4 inch) of excess material to be extended past grip section. Use of that reference produced 3 unsuccessful designs for this application. The following sections of this report describe improvements that were made to further address gripping issues, including the novel coupon design developed.

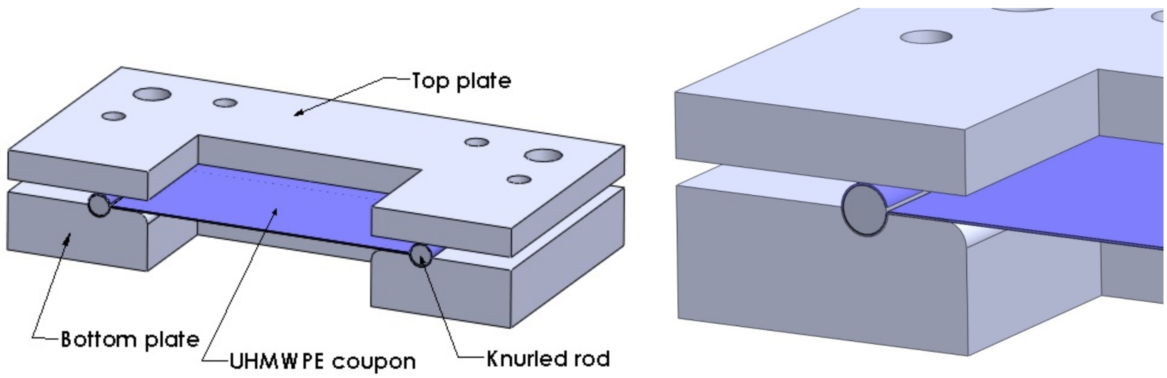

Fig. 3   Sectioned view of test fixture with UHMWPE coupon. View on right is a blow-up of the sheet material and a knurled rod.

1.2   Novel Test Coupon Concept and Preliminary Results

Figure 4 shows the 3 different specimen configurations that were conceptualized to be adapted into the new clamping fixture. These 3 configurations were all tested with the tabs wrapped around the knurled rods as described above. The variation was in the tab size and direction of the cut in the coupon to create the tab. The results from all 3 coupon designs were inconsistent as slippage of the coupons in the fixture remained to be a source of undesirable variability in the loading. Figure 5 shows a post-test photograph of coupon Design 1 and Design 2. These images reveal that some degree of slippage of the cross-ply material occurred. The black and red reference lines were traced with a Sharpie marker along the inside edge before and after testing, respectively. If no slippage had occurred, these lines would be similar to each other. The damage to the coupons was limited as ram displacement was stopped once a substantial drop in the load response was observed.

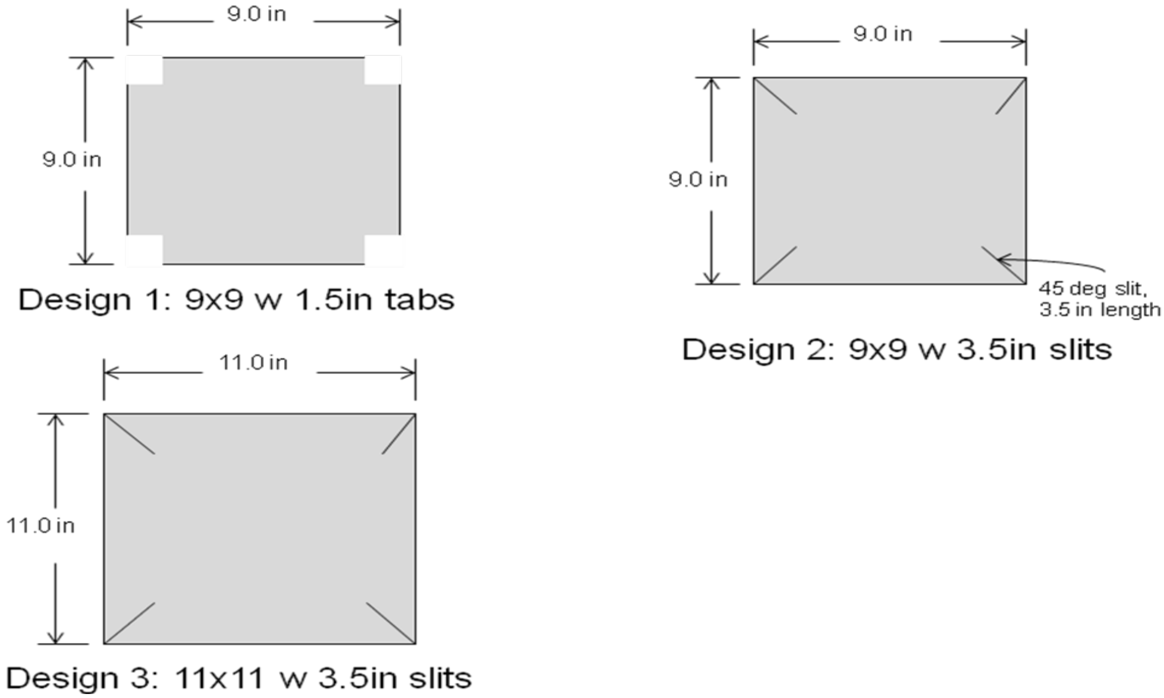

Fig. 4 Initial designs of 3 different coupon dimensions and shapes

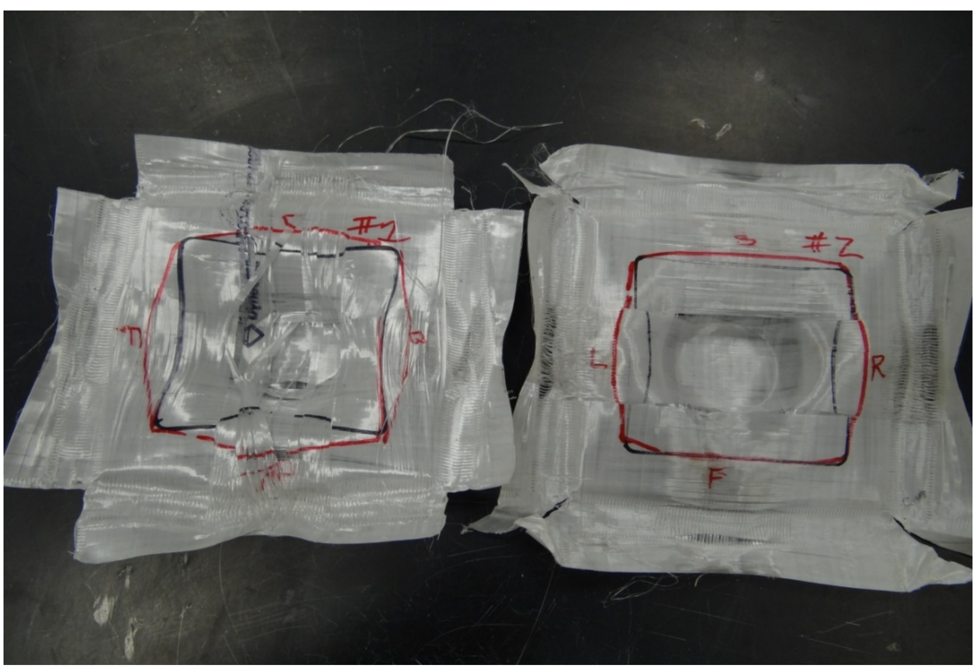

Fig. 5 Post-test photographs of coupon Design 1 and Design 2

Figure 6 provides a summary of the results from the initial test methodology and coupon designs. The punch force versus displacement shows a significant amount of variation. Results were inconsistent and slippage was evident from observation for each test coupon. Any indication of slippage invalidates the test data.

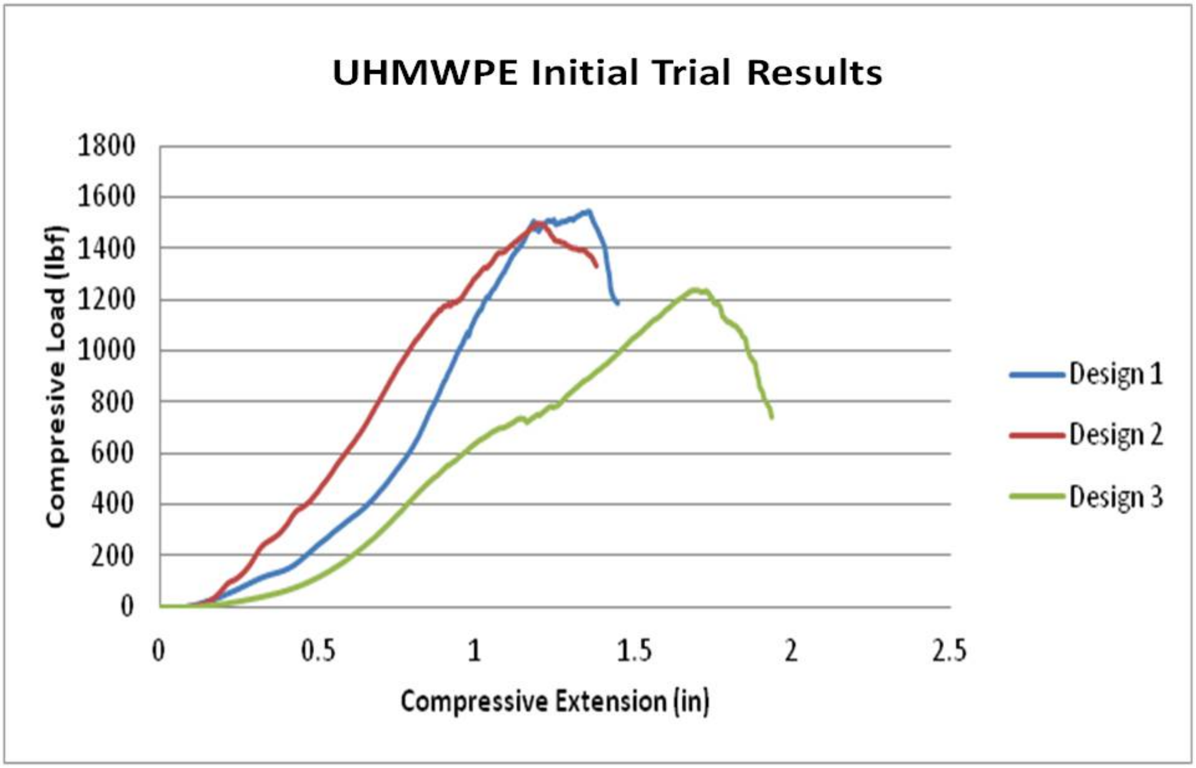

Fig. 6 Initial test results of UHMWPE cross-ply from different coupon designs

1.3 Test Fixture and Coupon Redesign

The coupon geometry was changed to a larger cruciform design as seen in Fig. 7 (the dimensions shown are in inches). The longer ends allowed the coupon to be wrapped around the knurled rods, which have been relocated to the outer plate edge changing the clamping means of the fixture. The cruciform ends are then inserted back in between the 2 plates gripping the UHMWPE sheet in place as seen in Fig. 8.

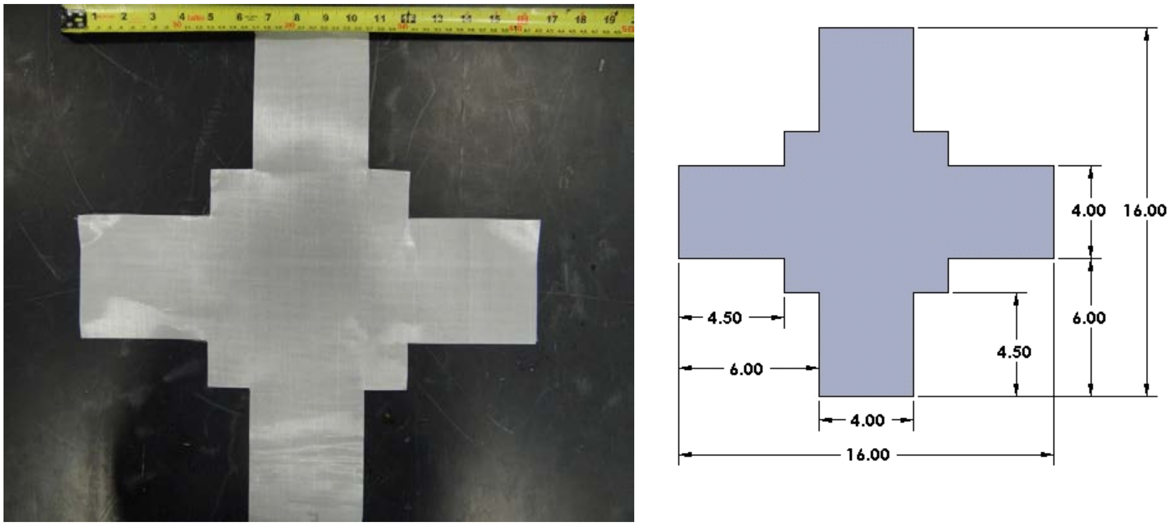

Fig. 7 16 inch × 16 inch cruciform coupon in photograph and computer-aided design (CAD)

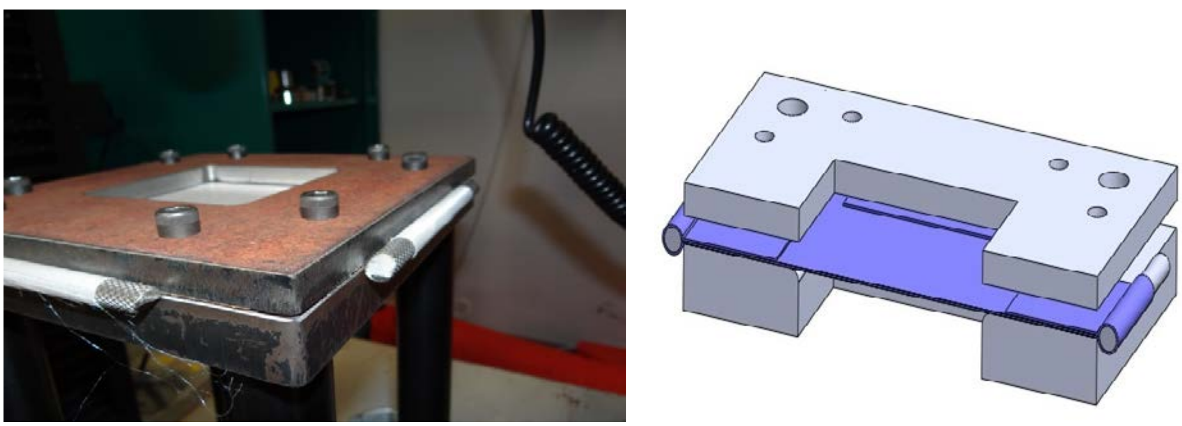

Fig. 8 Photograph: relocated knurled rods at outer plate edge with new cruciform geometry and wrapping of coupon. CAD cross-section: top plate raised to show coupon tabs.

An adhesively bonded 60-grit sandpaper (as referenced in ASTM D6241-04) was applied to the top and bottom plates' contact surfaces to further assist in stopping slippage, as in Fig. 9. The ends of the cruciform are pulled through the inner opening to draw the material taut to remove any wrinkles or slack in the coupon. A series of incremental bolt-torque tests were performed to determine the necessary torque on the 3/8-inch grade-8 bolts clamping the coupon between the top and bottom plates of the fixture. A torque of 40 ft-lb was determined to be sufficient to eliminate slippage while under load without exceeding the bolt strength.

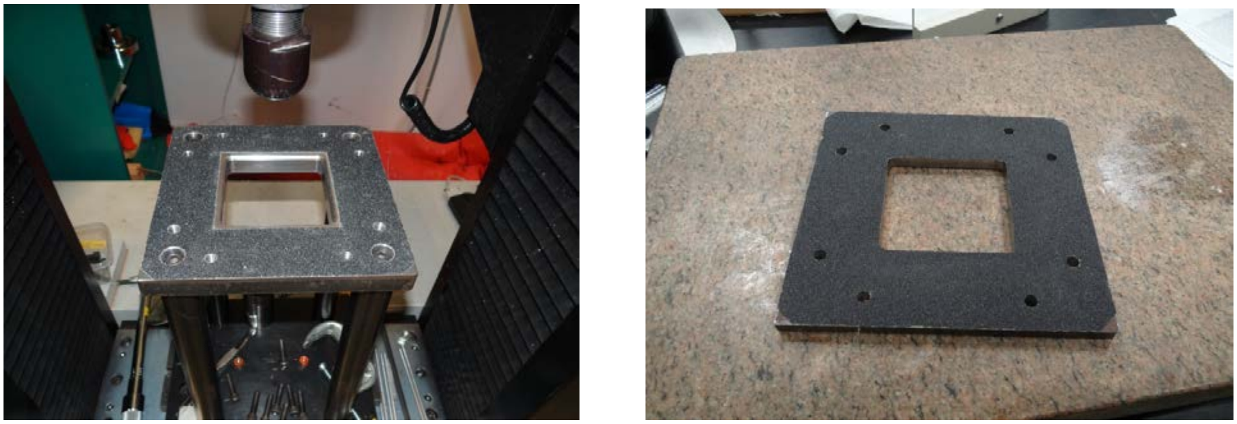

Fig. 9 60-grit surface coating of top and bottom plates

1.4 Punch Tool Geometry

In addition to enhancing the gripping techniques for UHMWPE materials, the effects of punch-tool geometry were investigated to assess the unconventional use of a rectangular fixture to perform the compressive testing. It was desirable to have a large punch-contact surface to provide more uniform loading on the coupon. It was also desirable to have some radius on the punch to promote uniform contact with the specimen as the loading progressed. A large radius was used to minimize the tendency to separate or perforate the plies within the coupon and to provide a smooth transition at the interface where the coupon left the punch.

Three punch geometries were examined. One was a hemispherical shape with a 1-inch-radius end. The second has a flat bottom with a small radius (0.098 inch) at the cylinder wall as per the ASTM 6241. Lastly, the third punch had an end radius of 8 inches with a transitional radius of 0.1875 inch. Figures 10–12 show the sectional drawing views (with dimensions in inches) and the top and bottom test views of each punch head that has traveled to a displacement of 0.8 inches. The regions of contact between the punch and the test coupon can be seen in the drawings. The flat punch yields the highest contact area, followed by the 8-inch-radius end, and finally the hemispherical shape with significantly less area of contact. All 3 punch heads were 2 inches in diameter and fabricated out of hardened steel. Three different punch designs were evaluated by systematically conducting a series of load experiments for each punch on the new cruciform-shaped coupon.

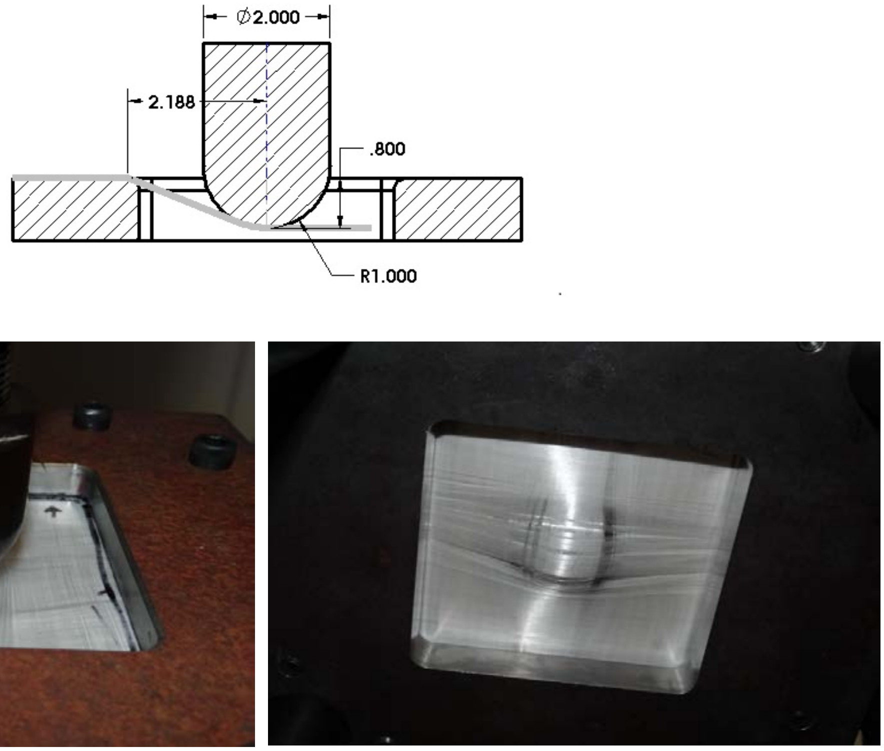

Fig. 10 Hemispherical 1-inch-radius end punch's detail and top and bottom views

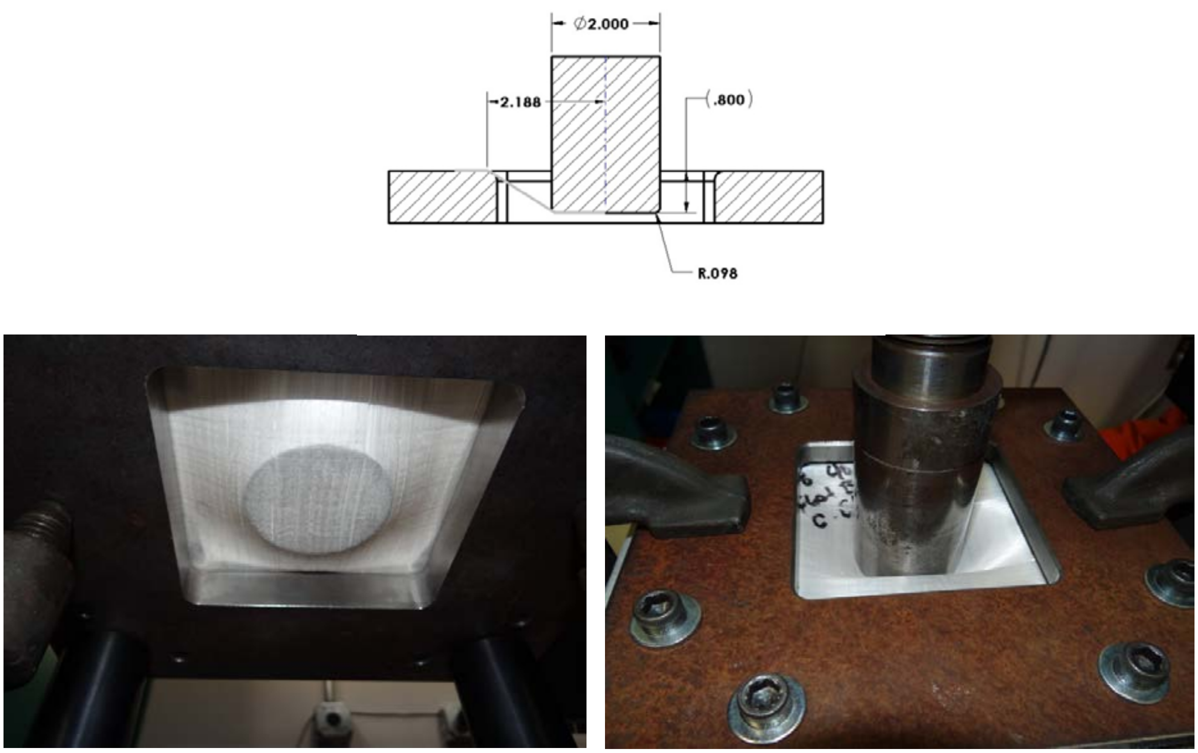

Fig. 11 Flat-ended punch's detail and top and bottom views

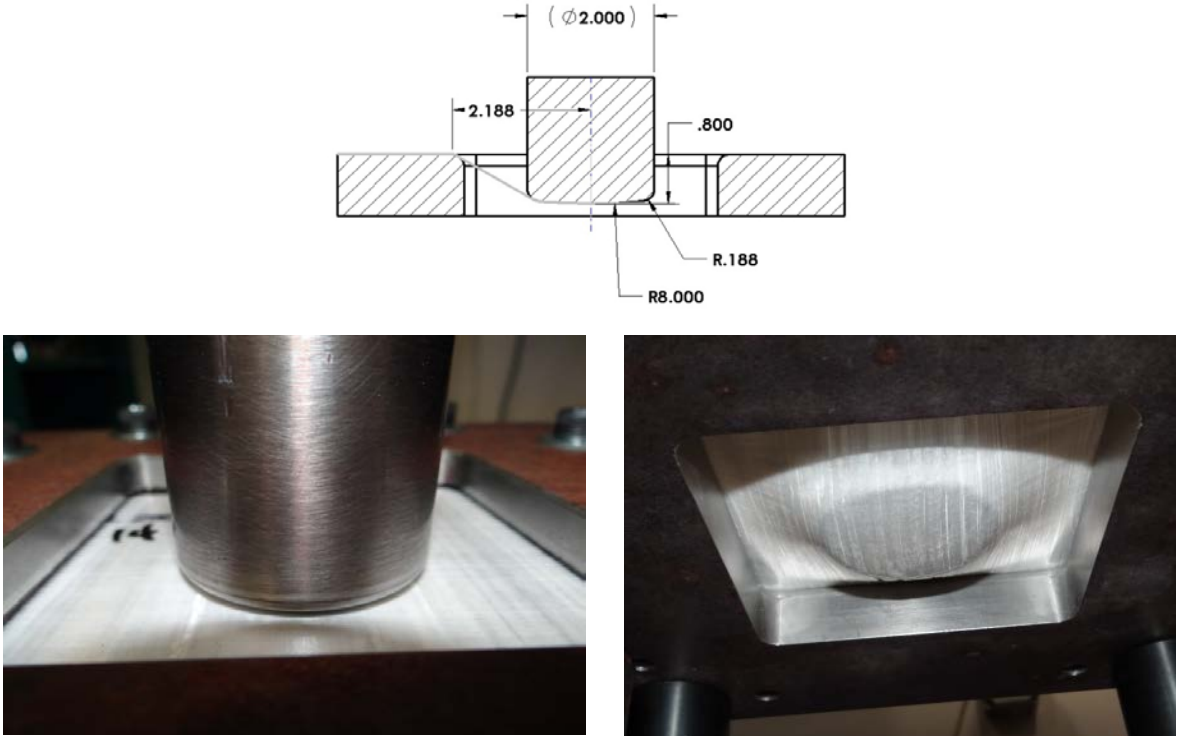

Fig. 12 8-inch-radius punch’s detail and top and bottom views

Distinct demarcation of the coupon from edges formed by the end and side walls of the punch raised concerns that the flat-bottom punch may not test uniformly or could create undesirable loading at its edge. The hemispherical 1-inch punch produced noticeable separations of the fibers within the layers and had more variability in failure loads. This is largely due to the interaction of the relatively small radius with the 0/90 layup of the plies, also seen in Fig. 11.

2. Initial Test Trial Results

Experiments with the new gripping technique and different punch shapes were conducted on unprocessed UHMWPE cross-ply materials in the cruciform-shape geometry as previously discussed. The load frame’s cross-head speed was set to 2 inch/minute as referenced in ASTM D 6241. Results of the load-displacement plots for each punch shape are shown in Fig. 13. The flat-ended punch obviously produced the highest load to failure as well as showing an effectively stiffer response. The results from the 8-inch-radius end punch reveal a drop of 20% in the peak load and that the 1-inch-radius punch produced the lowest load to failure. The flatter tool has less sliding and engages more fibers. Typical damage-pattern impressions on the coupons, due to interaction with the punch, are shown in Fig.14a–c for the hemispherical, 8-inch-radius, and flat-ended punches, respectively.

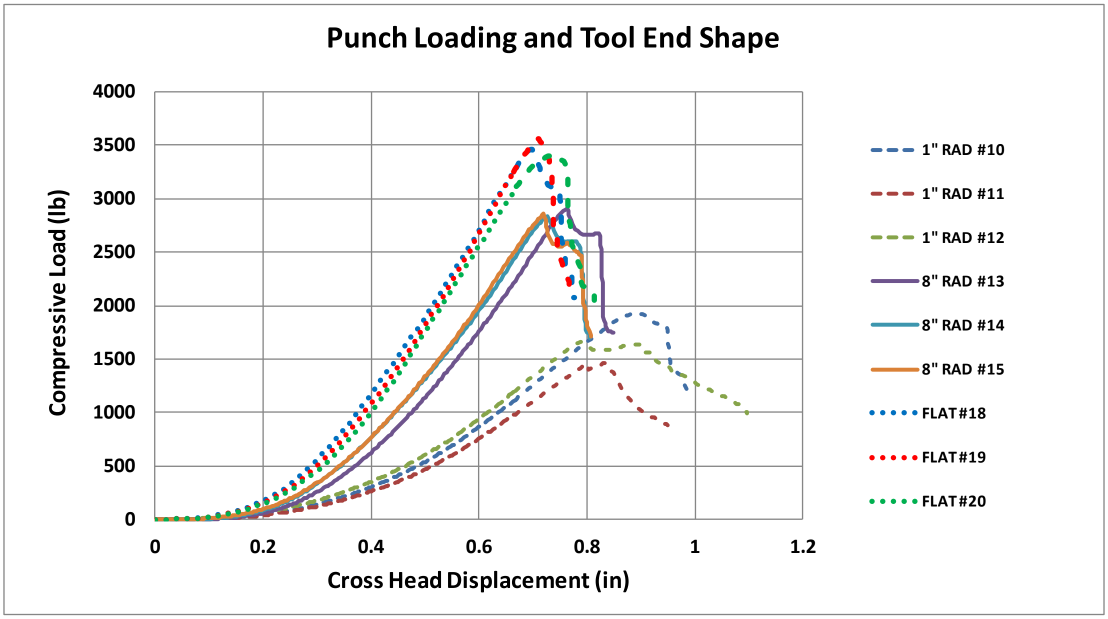

Fig. 13 Load-displacement curve vs. punch geometry

(a)

(b)

(c)

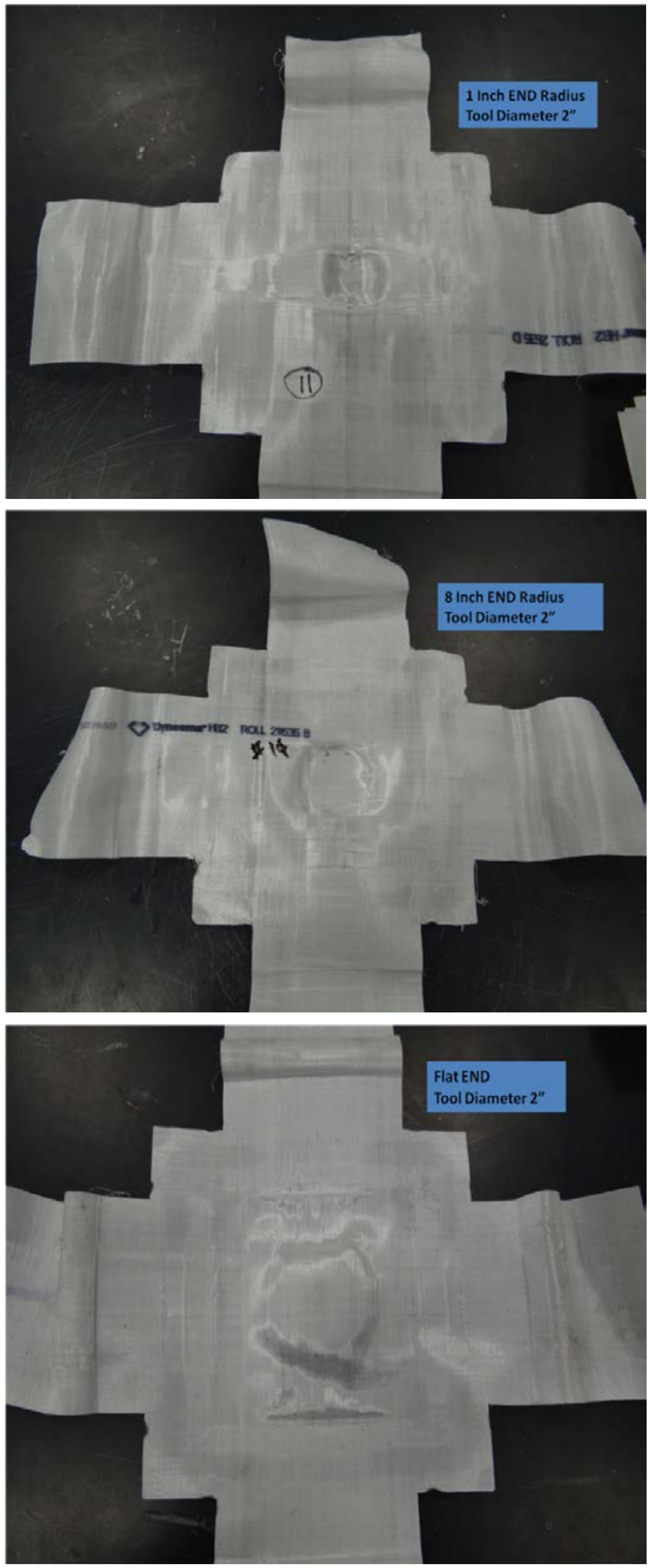

Fig. 14 Damage-pattern impressions made on the UHMWPE coupons: a) 1-inch-radius hemispherical, b) 8-inch-radius, and c) 1-inch-radius flat.

Table 1 shows the average maximum failure load and apparent stiffness or slope of the load-displacement curve for each of the punch geometries along with the associated variations. The term "apparent stiffness" in this report is defined as the change in load relative to the change in cross-head displacement. While the sampling sizes were limited to 3 tests for each condition, the least amount of variation in maximum load to failure occurred with the use of the 8-inch-radius punch. The 1-inch-radius hemispherical punch's head had a significantly lower load to failure with more variation in this load due to the fibers sliding off the rounded punch.

The results also indicate that for a given punch shape, the variations of the apparent stiffness are less than the variations of the loads to failure. The apparent stiffness was also found to be greatest for the flat punch and lowest for the 1-inch-radius punch. The flatter tool has less sliding and has more fibers engaged. The relative differences in apparent stiffness for the 3 punch geometries are similar to that of the differences in load to failure.

There are substantial differences in the way the hemispherical shaped punch and the flat-end punch interact with the UHMWPE coupon. This is probably due to the effective contact area between the steel punch and the UHMWPE material. The concern that the flat-end punch would have more detrimental edge effects than the 8-inch-radius punch did not bear out in the results. Based on these results, the flat-end punch would be used for all tests going forward due to its higher peak loads before lamina failure. Step-by-step test procedures are detailed in the Appendix.

Table Average, Standard Deviation, and percentage of punch-tool maximum load

Shape	Avg Max Load (lb)	SD Max Load (lb)	SD % of Load Avg	Avg Slope (lb/in)	SD Slope (lb/in)	SD % of Slope Avg
Hemi	1687	235	13.9%	3863	290	7.5%
8-in RAD	2867	40	1.4%	7019	309	4.4%
Flat	3478	78	2.2%	8277	307	3.7%

3. Fixture and Process Improvements

Another enhancement to achieve consistent grip clamping for a range of UHMWPE materials types was also investigated. Both upper and lower plate surfaces with the 60-grit adhesive-backed sandpaper were replaced with steel plates having a 1/16-inch diamond-serrated finish machined directly into the contact surfaces. Figure 15 shows the CAD and photograph of the finished plates with the diamond-serrated pattern. It was found that the diamond-serrated surface finish substantially increased the clamping efficiency (i.e., decreased the material slippage). This produced more consistent failure loads. (The grooves in the base plate are artifacts of past

revisions and are no longer needed for future fixture construction.) The serrations used were about .025-inch deep with a pitch of .05 inch as shown in the detail view in Fig. 15. Figure 16 shows a comparison of 3 separate tests with the diamond-serrated plates and a typical sandpaper test on UHMWPE material. Use of the diamond-serrated pattern produced an increase in load of about 20% over the original sandpaper design. It was also found that the repetitive torquing and untorquing of the bolts developed galling and friction between the bolt and washer. This friction reduces the torque employed to apply clamping force to the fixture. This problem was reduced though the use of 2 grade-8 hardened washers under each bolt head and exchanging them for new ones every 15–20 coupons. Using this procedure the fixture has maintained the desired clamping grip load.

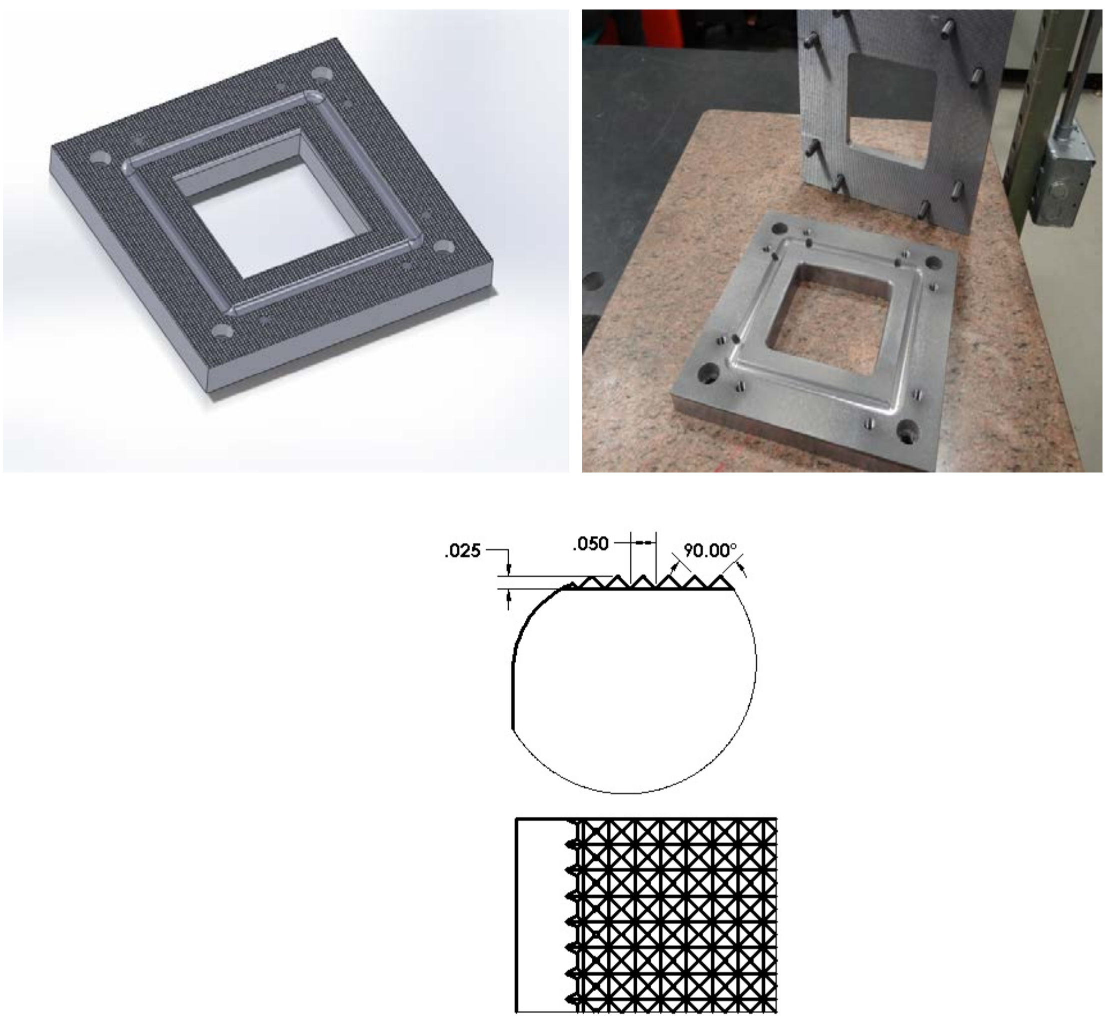

Fig. 15 SolidWorks[3] CAD view and photograph of diamond-serrated plate surface and CAD details

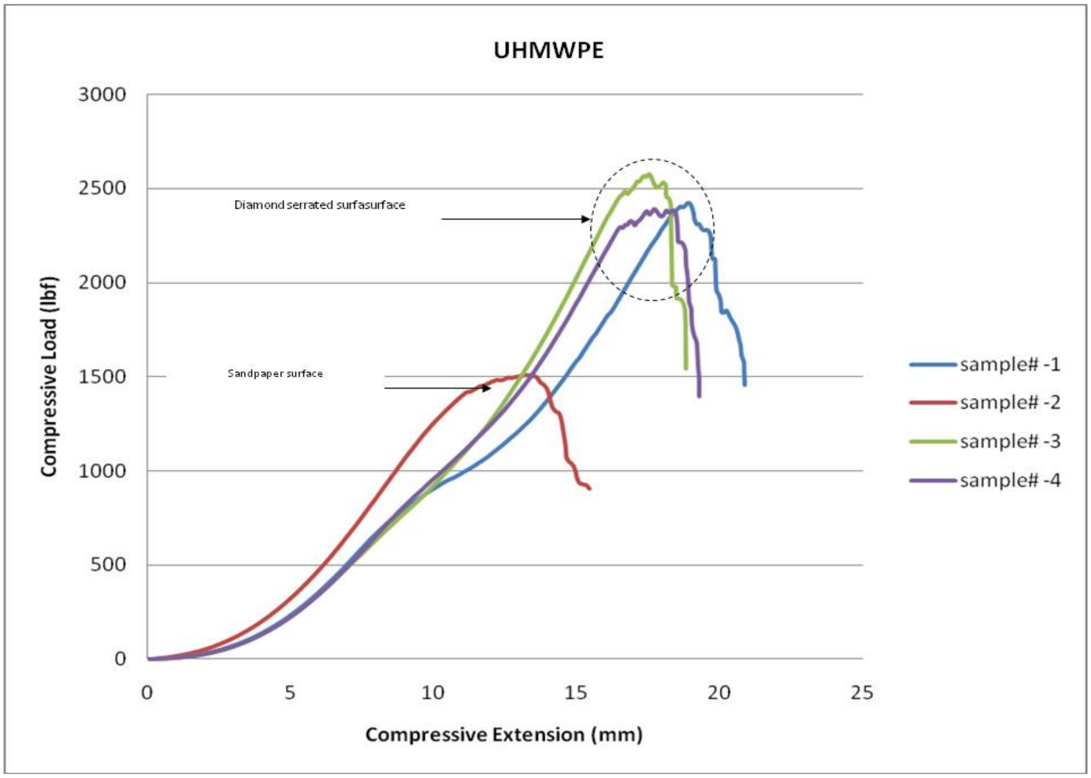

Fig. 16 Punch-test results for UHMWPE material with the 60-grit sand paper vs. diamond-serrated surface finish

4. Summary

A novel punch-test method was developed for evaluating unprocessed UHMWPE cross-ply sheet material. Development of this test procedure involved design of a gripping strategy to eliminate slippage of the material and the establishment of preferred punch-shape geometry. There are substantial differences between the interaction of the hemispherical punch and the UHMWPE sheet and the interaction of the flat-ended and 8-inch-radius ended punches. The flat-ended punch provided the highest load to failure and effective stiffness. The coupon geometry was redesigned to a larger cruciform pattern with longer ends that allows it to be wrapped around knurled rods located on outer-plate edge. The use of a machined diamond-serrated surface for gripping was found to be more desirable experimentally than adhesively attached sandpaper's grit in light of consistency of results and ease of performing the testing. The preferred texture or coarseness of the diamond serrations could be dependent upon the material and thickness of the coupons being tested. It was also noted that most UHMWPE sheet material was sensitive to relaxation/creep after the coupon was torqued into fixture and let stand for periods greater than 10 minutes. The data on material responses to testing will be published in future reports.

5. References and Notes

1. MIL-DTL-32398. Laminate: cross-plied ultra-high molecular weight polyethylene (UHMWPE) unidirectionally reinforced plastic armor. Aberdeen Proving Ground (MD): Specifications and Standards Office, US Army Weapons and Materials Research Directorate; 2013 Jun 9.
2. ASTM D 6241 Standard test method for the static puncture strength of geotextiles and geotextile-related products using a 50-mm probe. West Conshohocken (PA): ASTM International; 2009.
3. Dassault Systemes SolidWorks Corp., 300 Baker Avenue Concord, MA 01742.

Appendix. Punch Test Procedure

Punch Test Procedure

1. Mount the bottom test-frame fixture to the load test frame. Ensure the bottom test fixture is properly bolted and tightly secured to the load test frame and that the center axis of the fixture is aligned with the load axis of the test frame.
2. Affix the punch head to the load cell. Be sure the load cell meets the load capacity for the test.
3. Inspect the fixture for damage and residual material in between the serrations. Clean the surfaces, if necessary.
4. Place the coupon on top of the bottom fixture. Position and center it relative to the test fixture.
5. Position the top plate over the test specimen and rest it on a wedge to leave an approximately 3/8-inch gap between the bottom and top plates.
6. Place the knurled rod on top of the test specimen where it extends from the test fixture, and bend the material over the rod. Insert the rest of the material back between the 2 plates. Repeat for the other 3 sides. There should be enough material so that it may protrude into the fixture.
7. Remove the wedge and lower the top plate of the test fixture and snug the bolts.
8. Torque each bolt (3/8 inch, grade 8) to 40 ft-lbs. tighten the bolts in crisscross pattern. Torquing the bolts should pull the material taut. Note: 2 thick, hardened washers should be placed on each bolt so that the washers are between the top plate and bolt head to reduce friction.
9. Lower the punch head until it comes in contact with the top of the test specimen.
10. Begin testing with the crosshead speed at 2 inches/minute. Record the load, displacement, and time.
11. Stop the test when the load drops off significantly.
12. Take the test specimen out of the fixture after removing all of the bolts securing the top plate.
13. Inspect the fixture for damage and residual material in between the serrations. Clean the surfaces, if necessary.
14. Repeat Steps 3 through 13 for the next test coupon.

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